Preprint
UCRL-JC-144947

Using Laboratory Measurements of Electrical and Mechanical Properties to Assist Interpretation of Field Data from Shallow Geophysical Measurements

H. Bertete-Aguirre, P.A. Berge, and J.J. Roberts

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

This article was submitted to Symposium on the Application of Geophysics to Engineering and Environmental Problems, Denver, Colorado, March 4-7, 2002

November 30, 2001

Paper to be submitted for **Paper** presentation at the *Symposium on the Application of Geophysics to Engineering and Environmental Problems*, to be held in Las Vegas, NV, Feb. 10-14, 2002

USING LABORATORY MEASUREMENTS OF ELECTRICAL AND MECHANICAL PROPERTIES TO ASSIST INTERPRETATION OF FIELD DATA FROM SHALLOW GEOPHYSICAL MEASUREMENTS

Hugo Bertete-Aguirre, Patricia A. Berge, Jeffery J. Roberts
Lawrence Livermore National Laboratory, Livermore, CA
(e-mail hba@llnl.gov, berge1@llnl.gov or roberts17@llnl.gov)

Abstract

Reconstruction of shallow subsurface structure from geophysical data is a central problem for many environmental and engineering applications. We observe that for shallow soil distributions, seismic data alone or electrical data alone may provide a good reconstruction of the subsurface. We show that using joint seismic and electrical data will improve the reconstruction of shallow structure. Our results emphasize that the availability of techniques for making laboratory measurements of ultrasonic velocities at low pressures in unconsolidated materials and the ability to measure complex impedance in similar samples are key elements of this approach.

Introduction

The measurement of geophysical properties of shallow areas can be important to discriminate soil features under ambiguous environmental situations. Interpretation methods in common use for geophysical field data and current methods of combining various types of geophysical field data were developed for oil industry applications and are not optimized for the shallow depths and unconsolidated materials of environmental applications. Laboratory data collected for soils at low-pressure conditions appropriate to the near-surface can be very useful for developing new interpretation techniques for geophysical field data from environmental sites.

Laboratory measurements of porosity, permeability, and complex impedance in the frequency range of 0.01 to 100 kHz are available for fully-saturated artificial soils made from mixtures of Ottawa sand and Wyoming bentonite, the same artificial soils for which we have ultrasonic velocity measurements (Berge et al., 1999; Bonner et al., 1999, 2001; Zimmer et al., 2001; Wildenschild et al., 2000). In previous work (Bertete-Aguirre and Berge, 2001), we developed an inversion algorithm for inferring soil composition given seismic compressional (P) and shear (S) wave velocities, using laboratory ultrasonic velocity measurements to constrain the mapping from velocities to lithology. In this paper we use the laboratory velocity and electrical properties data to investigate how additional geophysical data may improve underground imaging of shallow environmental sites.

Methods

The laboratory velocity data collected using recently-developed techniques include uniaxial measurements of ultrasonic velocities for dry, saturated, and partially-saturated sands and sand-clay mixtures made at pressures below approximately 0.1 MPa (Aracne-Ruddle et al., 1999; Berge et al., 1999; Bonner et al., 1999, 2001). We also used data from Wildenschild et al. (2000) for electrical properties for sand and sand-clay mixtures measured using the four-electrode method.

The samples for the ultrasonic and electrical experiments were made by combining various amounts of Ottawa sand and Wyoming bentonite. Sample construction and laboratory measurement techniques are described in detail in Aracne-Ruddle et al. (1999) and Wildenschild et al. (2000). The laboratory data we use in this paper are compressional-wave velocities (Vp) measured at pressures appropriate for the shallow subsurface, and electrical conductivities (σ) with fluid salinities analogous to ground water. We assume the velocity changes mainly with depth (pressure) and clay content, but we neglect fluid effects for low saturation. For the electrical properties, we assume conductivity changes mainly with saturation and clay content, but we neglect depth (compaction) effects for the shallow subsurface.

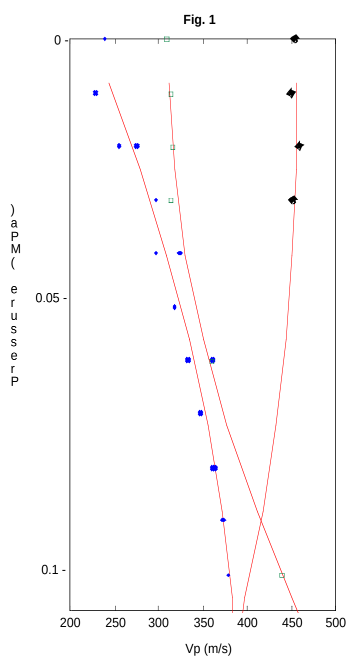
We developed an inversion code to obtain the soil distribution in the shallow sub-surface from compressional-wave velocity (Vp) and conductivity (σ) data. The code minimizes the misfit between the observed (simulated field data) Vp, σ pairs of data in the region of interest and Vp, σ for known soil compositions.

Soil Distribution Models

For the purposes of this work, we used the sand-clay laboratory data to build two realistic field models in 2-D, simulating two sites having interbedded sands and silty sands.

We used laboratory measurements of soil velocities at low pressures to develop relationships between soil velocities and soil composition. The laboratory velocity measurements were made at pressures between 0 and about 0.1 MPa (about 16 psi) in pressure increments of about 0.01 MPa (about 1.5 psi), and represent the top few meters of the subsurface. The laboratory samples were intended to represent silty sands and sandy soils, for simple systems under controlled conditions in dry and fully saturated cases. Pore fluids were various $CaCl_2$ solutions and filtered, de-ionized water. Velocities were also measured in sand samples with various degrees of partial saturation (Bonner et al., 2001). In this paper we use only dry samples to simulate the field data for the vadose zone, since velocity does not vary greatly for low saturation (about 10% to 50% in our example). **Figure 1** presents the laboratory measurements of Vp as a function of pressure for three sand-clay samples. Accuracy was limited to 20% at the lowest stresses near 7 kPa, but improved with signal amplitude to about 3% for compressional (P) waves and 10% for shear (S) waves at higher stresses. Precision in timing the arrivals was about 1% for P and 2 to 5% for S arrivals in most cases. For purposes of the inversion we assumed all the data had the same quality, but it would be possible to incorporate weighting factors based on laboratory measurement uncertainty in a future refinement of our inversion code. The sand-clay sediments have different velocity gradients that change with pressure. Gradients depend on the amount of clay and on the sample packing. We can use second-order polynomial fits to the data to obtain continuous estimates of Vp vs. pressure and to extrapolate Vp to pressures above 0.1 MPa for depths beyond 5 m. Note that some of the Vp values measured in the laboratory are extremely low, below the speed of sound in air. Field seismic studies also have observed very low Vp values, e.g. 130 m/s in the upper few cm of soil and 180 m/s in the next few tens of cm (Baker et al., 1999) and 150 to 170 m/s in the top m (Bachrach et al., 1998).

Wildenschild et al. (2000) measured complex impedance in the frequency range of 0.01 to 100 kHz for fully-saturated soil samples made from mixtures of Ottawa sand and Wyoming bentonite, as for the velocity samples. They used their data to investigate how the amount and arrangement of clay affect geophysical properties. Pore fluid conductivity was varied from about 5 x 10^{-3} S/m to about 6 S/m, using various solutions of filtered deionized water and NaCl or $CaCl_2$. They designed a technique that allowed them to make electrical measurements using the 4-electrode method described by Olhoeft (1985), and to measure hydraulic permeability by a constant flow technique without removing the sample from the measurement apparatus. These electrical measurements were made at room temperature and at pressures up to about 0.4 MPa, equivalent to about the top 10 to 20 m of the subsurface. Since porosity does not vary greatly at these pressures, conductivity is not a strong function of pressure, so we will neglect depth effects. Details of experimental methods, results, and uncertainties for electrical properties measurements, porosities, and permeabilities of these samples are described in Wildenschild et al. (2000). We need information on conductivity for the case of partial saturation, to represent soil conditions in the vadose zone. We used the Waxman and Smits equation as modified by Chesnut and Cox (1978) (see also Ramirez et al., 1993; Roberts and Lin, 1997) to describe conductivity as a function of saturation for three sand-clay samples from Wildenschild et al. (2000) with 0.1 N $CaCl_2$ pore fluid (**Figure 2**). Note these are single-frequency results at 1 kHz. The conductivity varies with saturation and clay content.



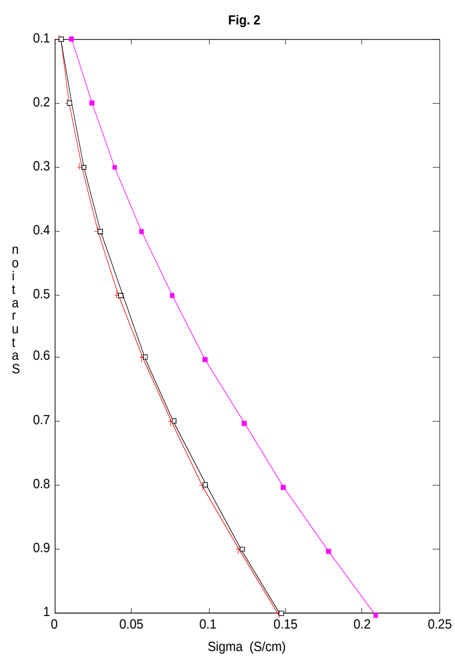


Figure 1 — Vp vs. pressure measured in laboratory for pure sand sample (curve on left with small blue dots); sand with 3% clay (curve on right with large black dots); sand with 10% clay (middle curve with green squares).

Figure 2 - Conductivity as a function of saturation for three sand-clay samples with 0.1 N $CaCl_2$ pore fluid: pure sand (curve on right with pink squares); sand with 3% clay (curve on left with red + symbols); sand with 10% clay (middle curve with green circles).

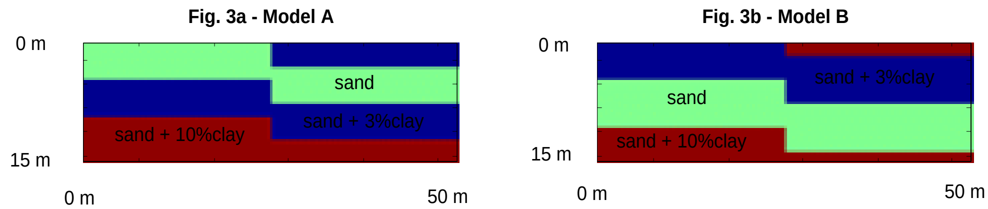
Our two different soil distribution models, Model A (**Figure 3a**) and Model B (**Figure 3b**), represent realistic field models of interbedded sands, silts, and clays at two hypothetical sites. **Figure 3a and Figure 3b** show soil type as a function of depth. The clay content in various layers is 0, 3, or 10% (as for laboratory samples in **Figure 1 and Figure 2**). The saturation in the subsurface varies linearly from 10% at the top to 50% at the bottom of each model. These models are 50 m wide and extend to a depth of 15 m.

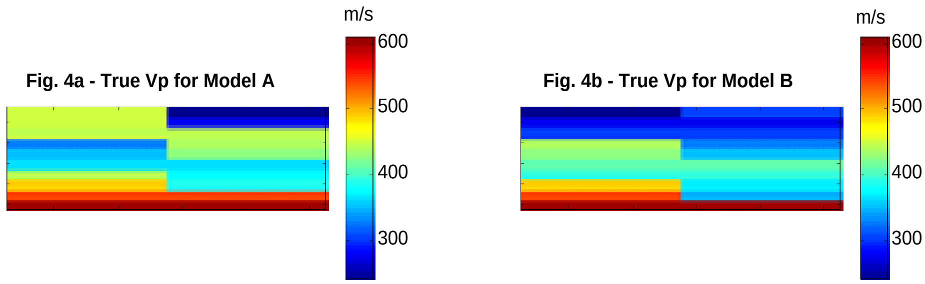
Synthetic Data from Laboratory Measurements

We simulate field data in two steps, first by using laboratory data to obtain synthetic velocity and conductivity distributions, and then by adding noise to simulate field data. In order to generate synthetic velocity and conductivity data, we use data measured in the laboratory **(Figure 1 and Figure 2)** for the different soil types of the interbedded soil models in **Figure 4a** and **Figure 4b**.

First, we generate the true 2D velocity distributions as a function of depth (**Figure 4a and Figure 4b**) for the interbedded soil models (**Figure 3a and Figure 3b**) by discretizing the modeled regions and by using data from laboratory velocity vs. pressure measurements to calculate the velocity changes with depth. The model discretization is performed by dividing the 15 m x 50 m region of interest using a grid having cells that are each 1.5 m in the vertical direction and 5 m in the horizontal direction. We used second-order polynomial fits to laboratory data to simulate velocities to depths of 15 m, assuming a lithostatic gradient of approximately 0.008 MPa/m.

Similarly, the true 2D conductivity distributions as a function of saturation (which varies linearly with depth) for Model A and for Model B (**Figure 5a and Figure 5b**) are obtained from the laboratory conductivity vs. saturation data of **Figure 2**.





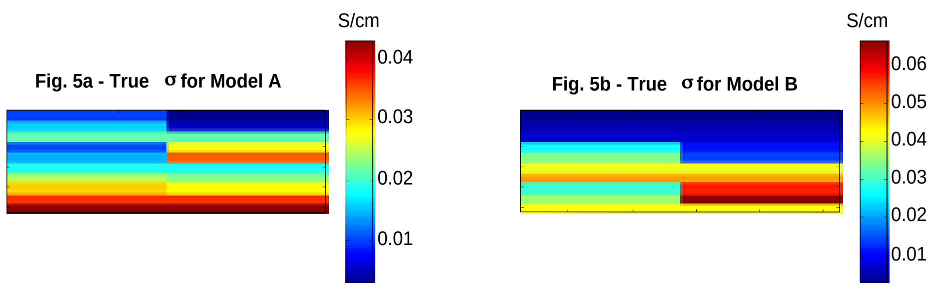


Figure 3a and Figure 3b - Two realistic field models of interbedded sands, silts, and clays at two hypothetical sites (Model A and Model B).

Figure 4a and Figure 4b - True 2D velocity distributions as a function of depth for the interbedded soil model A and model B.

Figure 5a and Figure 5b - True 2D conductivity distributions as a function of saturation (which varies linearly with depth) for Model A and for Model B.

Simulating Field Data

We simulate field data that could represent seismic surveys and field data from electrical or electromagnetic surveys. Since field measurements contain noise of various kinds (e.g., instrument, wind, cultural noise, etc.), we add random noise with a Gaussian distribution of ±10% to the true velocity distributions from **Figure 4a and Figure 4b**, to simulate field velocity data for Model A and Model B (**Figure 6a and Figure 6b**). Next, we simulate field conductivities (**Figure 7a and Figure 7b**) by adding ±10% noise with a Gaussian distribution to the true conductivity distributions from **Figure 5a and Figure 5b**.

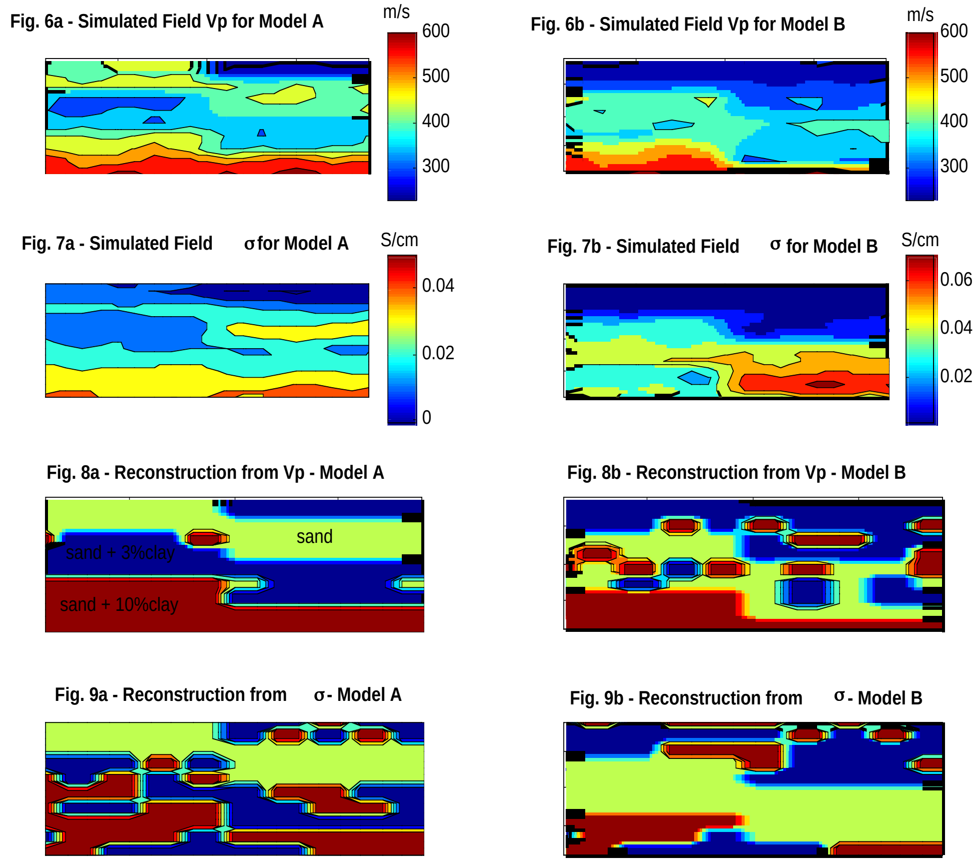


Figure 6a and Figure 6b - Simulated field velocity data for Model A and Model B.

Figure 7a and Figure 7b - We simulate field conductivities for Model A and Model B.

Figure 8a and Figure 8b - Inversion results obtained for Model A and Model B, respectively, when minimizing velocity misfits to reconstruct the soil distributions.

Figure 9a and Figure 9b - Inversion results obtained for Model A and Model B when minimizing conductivity misfits to reconstruct the soil distributions.

Reconstruction

We developed an inversion code to reconstruct soil distribution in the shallow subsurface from simulated field data. This code discretizes the subsurface region of interest in a 10 x 10 grid. Each cell in the grid is assumed to have constant soil composition, constant density, constant saturation, constant conductivity, and constant velocity. For a given point at a given depth, the code calculates the misfit between the observed noisy (+/-10% Gaussian random noise) data (seismic velocity or electrical conductivity) and second-order fits to laboratory ultrasonic velocity measurements at the pressure corresponding to that cell depth or conductivity at the appropriate saturation evaluated from laboratory conductivities and the modified Waxman and Smits equation. These laboratory data correspond to soil types used in the measurements. The code repeats this procedure for all available soil types, for Vp and σ, over all the cells in the entire grid. The code assigns a soil type to each cell by choosing the soil that gives the minimum misfit for the velocity, conductivity, or both, depending on what is specified.

Soil velocities at low pressures are nonlinear (e.g., Zimmer et al., 2001; Bonner et al., 2001), and thus a second-order fit was chosen instead of a linear fit.

Results and Discussion

In **Figure 8a and Figure 8b**, we present inversion results obtained for Model A and Model B, respectively, when minimizing velocity misfits to reconstruct the soil distributions. Similarly, in **Figure 9a and Figure 9b** we present results obtained when minimizing conductivity misfits to reconstruct the soil distributions for Model A and Model B. Then, **Figure 10a and Figure 10b** show results obtained when minimizing both velocity and conductivity misfits combined to reconstruct the soil distributions.

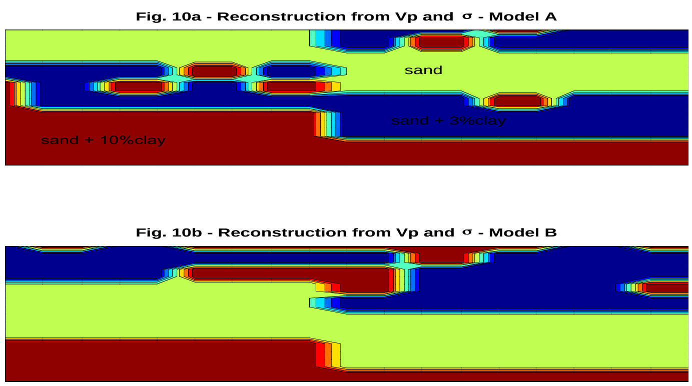


Figure 10a and Figure 10b — Inversion results obtained when minimizing both velocity and conductivity misfits combined to reconstruct the soil distributions.

We observe that in one case (Model A), the velocity data alone provide a useful reconstruction of the true model (compare **Figure 3a and Figure 8a**). In this case, the conductivity data alone did not successfully reconstruct the soil distribution (compare **Figure 3a and Figure 9a**). In the other case (Model B), however, the conductivity data alone provide a reliable reconstruction of the true model (compare **Figure 3b and Figure 9b**), whereas the velocity data alone were unable to properly reconstruct the true soil distribution (compare **Figure 3b and Figure 8b**). We can see that this is an example of how changes in the soil distribution affect which type of geophysical data may be more sensitive to structure. Neither type of geophysical data is inherently preferred, but if we combine both types of data we obtain the most reliable reconstruction in all the cases we studied (for example, compare **Figure 3a and Figure 10a**, **Figure 3b and Figure 10b**).

Conclusions

We observe that for shallow soil distributions, the seismic data alone or the electrical data alone may provide a good reconstruction of the shallow subsurface. We have shown that we can improve the reliability of reconstruction of shallow structures by using both seismic and electrical data, as we do not know in advance what our soil distribution is and which type of data would be preferred.

Our results emphasize that the availability of techniques for making laboratory measurements of ultrasonic velocities at low pressures in unconsolidated materials and the ability to measure complex impedance in similar samples are key elements of this approach. Future work using recent advances in field methods will allow us to obtain appropriate seismic and conductivity data for testing this method using real field data sets.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and supported specifically by the Environmental Management Science Program of the Offices of Environmental Management and Science.

References

Aracne-Ruddle, C. M., Bonner, B. P., Trombino, C. N., Hardy, E. D., Berge, P. A., Boro, C. O., Wildenschild, D., Rowe, C. D., and Hart, D. J., 1999, Ultrasonic velocities in unconsolidated sand/clay mixtures at low pressures: LLNL report UCRL-JC-135621.

Bachrach, R., Dvorkin, J., and Nur, A., 1998, High-resolution shallow-seismic experiments in sand, Part II: Velocities in shallow unconsolidated sand: Geophysics, 63, 1233-1284.

Baker, G. S., Steeples, D. W., Schmeissner, C., and Macy, B. K., 1998, In-situ, high-resolution P-Wave velocity measurements within 1 m of the Earth's surface: Technical Program for the Society of Exploration Geophysicists International Exposition and 68th Annual Meeting, held in New Orleans, LA, Sept. 13-18, 1998.

Berge, P. A., Berryman, J. G., Bonner, B. P., Roberts, J. J., and Wildenschild, D., 1999, Comparing geophysical measurements to theoretical estimates for soil mixtures at low pressures: LLNL Report UCRL-JC-132893, in Powers, M. H., Cramer, L., and Bell, R. S., Eds., Proceedings of the 12th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Oakland, California, March 14-18, 1999, Environmental and Engineering Geophysical Society, Wheat Ridge, CO, 465-472.

Bertete-Aguirre, H., and Berge, P. A., 2001, Recovering soil distributions from seismic data using laboratory velocity measurements: LLNL report UCRL-JC-141559, submitted to the Journal of Environmental and Engineering Geophysics.

Bonner, B. P., Berge, P. A., Aracne-Ruddle, C., Boro, C., Hardy, E., and Trombino, C., 1999, Ultrasonic characterization of synthetic soils for application to near-surface geophysics: LLNL report UCRL-JC-132889, in Powers, M. H., Cramer, L., and Bell, R. S., Eds., Proceedings of the 12th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Oakland, California, March 14-18, 1999, Environmental and Engineering Geophysical Society, Wheat Ridge, CO, 455-463.

Bonner, B. P., Berge, P. A., and Wildenschild, D., Compressional and shear wave velocities for artificial granular media under simulated near surface conditions (expanded abstract): LLNL report UCRL-JC-142935, Technical Program of the Society of Exploration Geophysicists International Exposition and Seventy-First Annual Meeting, Sept. 9-14, 200, San Antonio, TX, Vol. II, 1419-1422.

Chesnut, D. A., and Cox, D. O., 1978, Log analysis in a Rocky Mountain heavy oil reservoir: Transactions of the SPWLA Annual Logging Symposium, 19, Paper F, 1-15.

Olhoeft, G. R., 1985, Low frequency electrical properties: Geophysics, 50, 2492-2503.

Ramirez, A., Daily, W., LaBrecque, D., Owen, E., and Chesnut, D., 1993, Monitoring an underground steam injection process using electrical resistance tomography: Water Resources Research, 29, 73-87.

Roberts, J. J., and Lin, W., 1997, Electrical properties of partially saturated Topopah Spring tuff: Water distribution as a function of saturation: Water Resources Research, 33, 577-587.

Wildenschild, D., Roberts, J. J., and Carlberg, E. D., 2000, On the relationship between microstructure and electrical and hydraulic properties of sand-clay mixtures: LLNL report UCRL-ID-136122, Geophysical Research Letters, 27 (19), 3085-3088.

Zimmer, M., Prasad, M., Bonner, B. P., and Berge, P. A., 2001, Measurement of velocity and attenuation in shallow soils: UCRL-JC-145238, submitted to be included as a chapter in Near-Surface Geophysics, Applications and Case Histories, Vol. II, Butler, D. K., ed., Society of Exploration Geophysicists, Tulsa.